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The use of conditioned axial flow impellers to generate a current in test tanks

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ABSTRACT

It is necessary to build a new generation of current and wave testing tanks to simulate more realistic sea conditions. Methods for wave generation and absorption are well established but those for current generation in this context are less established. One means of producing a current is by using an axial flow impeller. Unfortunately an impeller introduces into the flow unsteady velocities with high shear, strong turbulent fluctuations and hub effects, alongwith the useful thrust. In the experiment presented here honeycomb flow conditioning placed immediately downstream of the impeller is used to reduce the turbulence present in the flow. An Acoustic-Doppler Velocimeter (ADV) is used to measure three velocity components at a rate sufficient to characterise turbulence. A novel experimental arrangement using brush seals allows the ADV to penetrate the duct without compromising the integrity of the duct. A large number of point measurements were used to construct velocity profiles at various positions downstream of the honeycomb. Three different impeller speed settings were tested to investigate wake evolution. The results presented will aid the development of numerical models and increase understanding of the flow downstream of a conditioned impeller.

1. Introduction

Due to an increase in interest in off-shore energy generation a new type of current and wave testing tank is required. Testing scaled energy generation devices such as tidal turbines require a consistent and controllable flow.

An attractive method of producing a consistent and controllable liquid flow is using an axial flow impeller. Many studies have already been conducted investigating propeller wakes in relation to ship propulsion systems (Felli et al., 2002; Stella et al., 2000a). Stella et al. (2000a) described the wake flow near a propeller as exhibiting unsteady velocities with high gradients, strong turbulent fluctuations, and hub effects. Although the impeller provides the necessary thrust to accelerate the fluid, the unsteady velocities, strong turbulent fluctuations, and hub effects have to be reduced to acceptable levels before the flow can be used for testing. In the immediate wake of a propeller the point velocities can fluctuate by $\pm 100\%$ of the mean velocity with turbulent intensities of up to 1000%. The velocity profile in the test section of a tank needs to be stable, one directional and developed with a turbulent intensity of less than 10%.

It is possible to condition the flow to achieve the required characteristics though this always results in a loss of energy. One example of a flow conditioning method that is applicable in the context of a current and wave testing tank is honeycomb.

Honeycomb is a device that can be used to condition and straighten a fluid flow. It is a collection of segregated flow paths aligned in the flow direction; it eliminates swirl (Baker, 2005) and reduces the turbulent eddy size. The amount of materials used in the cross-section normal to the flow direction is minimised to reduce the loss of energy.

The configuration shown in Fig. 1 uses honeycomb to reduce the eddy size as well as remove the swirl induced by the impeller. Energy could be recovered by using a stator stage before the honeycomb, but at the speed at which the impeller operates, this energy recovery would be minimal (Hoshino et al., 2004).

When designing a current and wave testing tank it is important to predict how the flow will evolve after passing through the honeycomb as this determines how much length is required to develop the flow before it can be introduced into the tank or turned. This work can be used to aid the prediction of that evolution. This work is also of interest to numerical modellers who may wish to use these results to validate models or reduce the size of their computations by using the measurements reported here as boundary conditions.

In this paper an experiment is set up to measure the flow characteristics of a conditioned impeller for several speed settings. The area of interest for this investigation is highlighted in Fig. 1. Measurements are made using an Acoustic-Doppler Velocimeter

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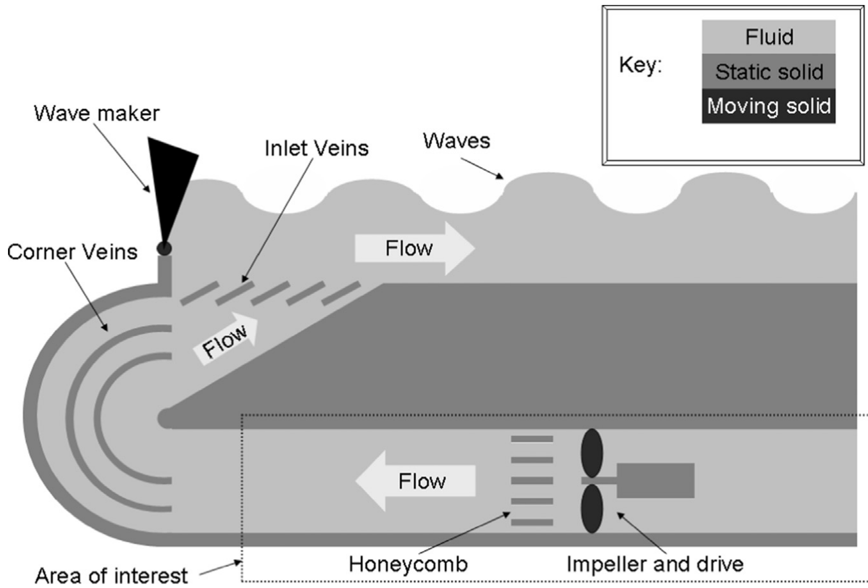

Fig. 1. Section through a potential current and wave testing tank.

(ADV) (Lohrmann et al., 1994). The ADV measures three components of velocity at a rate sufficient to characterise turbulence of the scale seen during these experiments.

1.1. Propeller wake analysis

Propeller wake analysis has been investigated many times as it is of great importance to those interested in the design of ships and their propulsion systems (Cenedese et al., 1988; Cotroni et al., 2000; Felli et al., 2002; Stella et al., 2000a).

In the past velocities in the propeller wake have been measured using Particle Image Velocimetry (PIV) (Cotroni et al., 2000; Di Felice et al., 2004; Felli et al., 2002; Stella et al., 2000a) and Laser Doppler Velocimetry (LDV) (Cenedese et al., 1988; Stella et al., 2000a, 2000b) due to the need for a non-intrusive measurement technique (Felli et al., 2002). PIV and LDV typically provide two components of velocity although it is possible to measure three components of velocity. LDV is a point velocity measurement technique. To assemble a true average measurement of the periodic and unsteady wake from a propeller it is necessary to relate the point measurement to the propeller position. To ensure that the measurement taken relates to a specific propeller position a triggering method called phase sampling is used (Cenedese et al., 1988).

PIV allows a simultaneous measurement of velocity through a 2D plane in the flow by comparing images of laser illuminated particles. Due to the length of time between each measurement image it is necessary to synchronise the imaging with the propeller position to produce good averaged data (Cotroni et al., 2000). Felli et al. (2002) used a stereo PIV setup to simultaneously measure three components of velocity. Stella et al. (2000a) measured two separate 2D planes sequentially then recombined the data in post-processing to give three components of velocity. ADV offers a point measurement equivalent to LDV and measures three components of velocity simultaneously. One of the potential issues with using an ADV is that the measurement head is intrusive. Although the ADV measures a volume centered 50 mm from the measurement head this intrusion might be an issue if significant swirl is present like that seen for an unconditioned propeller. The honeycomb used in this test should remove the swirl induced by the impeller; therefore the use of an ADV is acceptable.

Existing propeller wake studies measure downstream from the propeller face to the break-up of the helical tip vortex as these vortices dominate the flow behavior (Stella et al., 2000b). In these papers the noted measurement of the velocity profile evolution from the propeller does not stretch to the full recovery downstream. As this recovery distance is of critical importance to the design of water flumes this study needs to measure the wake further downstream of the propeller than the existing studies on unconditioned propellers.

Ducting is a method used to reduce thrust losses of a propeller in certain circumstances (Koç et al., 2009). The propeller in this experiment is mounted in a duct due to its being part of a current generation system, Fig. 1. Oweis et al. (2006a, 2006b) tested a very similar three-bladed, ducted propeller to the one reported here. The studies were however, concerned with tip-leakage flow, with no wake evolution data given. Koç et al. (2009) conducted an investigation into the velocity field of a impeller in air for which some wake data is provided. Nouri et al. (2011) also provided velocity field data for a impeller in air.

1.2. Turbulence measurement

Along with the wake evolution of velocity it is also important to have a knowledge of how the turbulence decays downstream of the honeycomb. There have been significant developments related to the accuracy of ADV in turbulent flows. Early ADV had problems relating to the raw signal being a combination of turbulent velocity fluctuations, doppler noise and signal aliasing, alongwith other disturbances. The data therefore could not be used without post-processing (Doroudian et al., 2007). Early ADV heads were also disruptive to the flow within the measurement volume (Rusello et al., 2006). Filtering techniques have been developed to improve the quality of velocity data for turbulent flows. An ADV requires three receivers to function in 3D. However the use of an extra receiver allows cross correlation of one of the measurement planes (Cea et al., 2007). This correlation data can be used to aid the filtering and improve accuracy (Rusello et al., 2006). Martin et al. (2002) found that the correlation value was affected by

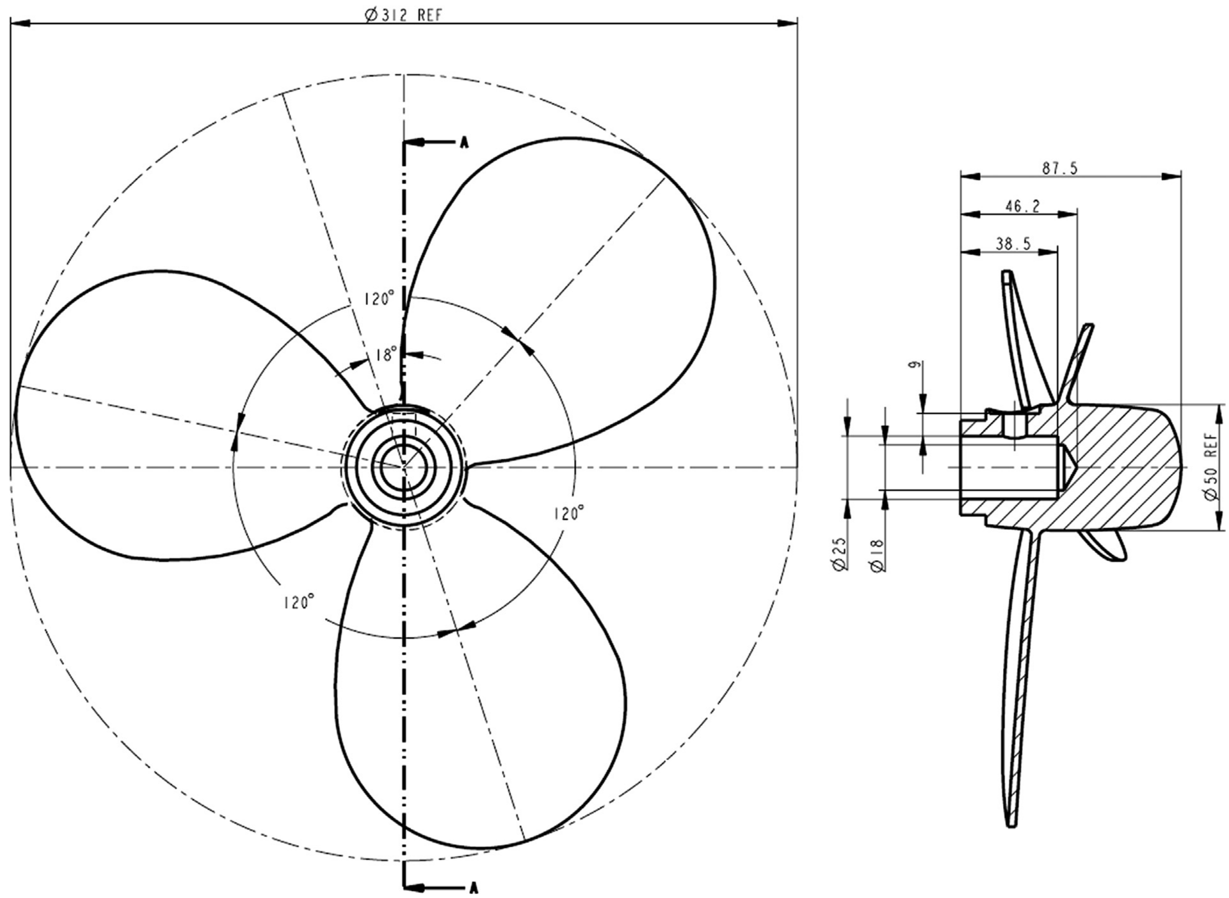

Fig. 2. Three-bladed propeller.

turbulence and provided filtering criteria for measurements in turbulent flows.

Rusello et al. (2006) used an ADV identical to that used here for an experiment within a highly turbulent flow and found that it consistently measured velocity within $\pm 4\%$ of PIV results.

2. Experimental method

To test the wake evolution of a conditioned axial flow impeller an experiment was set up where a conventional three-bladed impeller was machined to fit inside a 276 mm diameter duct, Fig. 2.

The propeller was attached to a watertight nacelle containing a DC motor. The whole assembly was supported and centered by four equally spaced arms. The maximum blockage ratio including the nacelle was 13.1%.

The Z axis of the Vectrino was aligned with gravity. However the test rig was angled at 1.6° and was higher at the downstream end. This small angle error is corrected in the results.

The honeycomb was secured at 3 mm from the end of the impeller hub as shown in Fig. 3. The honeycomb used was constructed from thin polycarbonate tubes with a 6 mm diameter and a length of 60 mm. Fig. 4 shows the honeycomb used.

A stream-wise slot was machined along the length of the top center of the duct to allow an ADV to pass through the wall. The slot was re-sealed using a brush seal (Fig. 5).

The experimental assembly was submerged in a 6000 mm × 2500 mm water tank with a depth of 300 mm. When in operation the experiment sets up a horizontal circulation within the test tank. By analysing the Y components of velocity the effect of the

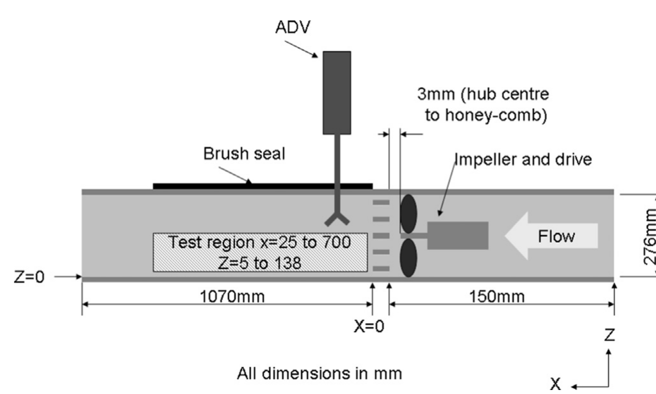

Fig. 3. Cross-section of experimental setup showing *XYZ* orientations and origins used throughout this paper.

circulation could be seen within the duct, and was found to be negligible. The duct entrance was close to the free-surface which could result in air ingestion. To minimise the chance of air ingestion a cowling was added to the inlet to only allow water of 150 mm below the free surface to be ingested.

The ADV was mounted on an automated traverse which is able to move in the *XYZ* directions. The gantry was programmed to move to pre-defined coordinates and has a positional accuracy of 0.1 mm.

Due to the axisymmetric nature of the flow being studied measurements were only taken in the lower half of the duct. The test region is shown in Fig. 3. By only testing in the lower half of the duct the chance of air bubbles entering the measurement volume from the brush seal or duct inlet is minimised.

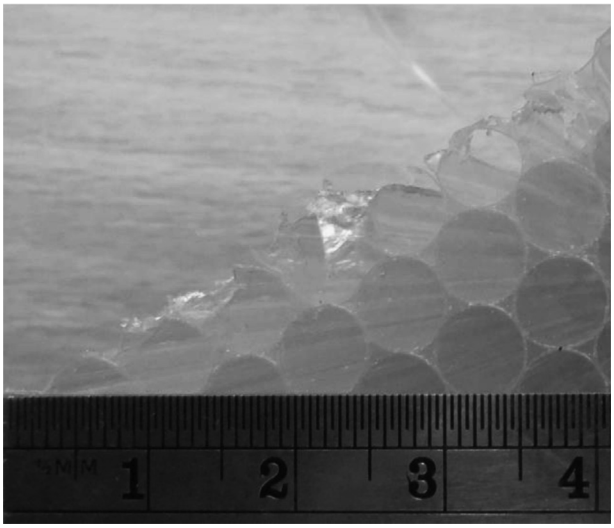

Fig. 4. Honeycomb, scale in mm.

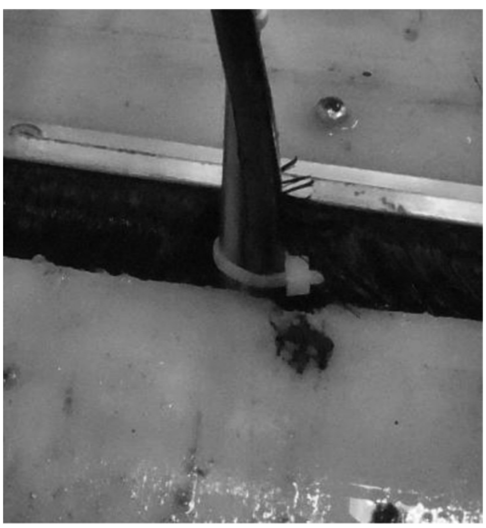

Fig. 5. Brush seals.

Symmetry was checked by taking a full profile across the center line and comparing velocity vectors on each side.

The test procedure involved measuring the full velocity profile for each X position and each speed setting before moving to the next downstream station.

2.1. Measurement setup

Point measurements of velocity components u, v and w were measured using a Vectrino+ADV (Nortek-AS, 2004). 6000 samples were taken for each point measurement. Tests with up to 30,000 samples were used to identify any long term flow variations and from these tests 6000 samples were found to be sufficient to remove long term flow fluctuations. Other authors such as Chanson et al. (2007) and Cea et al. (2007) have used up to 50,000 samples for turbulence measurement. Chanson et al. (2007) reported that 5000 samples were required to obtain the mean and standard deviations of velocity reliably. Turbulent intensity as used here is the ratio of the standard deviations of velocity and the mean velocity. Martin et al. (2002) stated that 2100 samples (70% of 3000) were required for reliable turbulence measurements.

The sampling rate used throughout this experiment was 50 Hz which is comparable with other investigators (Cea et al., 2007; Chanson et al., 2007; Martin et al., 2002; Rusello et al., 2006). The ADV measures a 6 mm diameter cylindrical measurement volume with a variable length which was set at 9.2 mm throughout this experiment. The ADV was set to measure the maximum velocity range available. This was found by Martin et al. (2002) to maximise the correlation value while measuring turbulent fluctuations and Rusello et al. (2006) also subsequently observed that. For the ADV used, the maximum range was ± 4 m/s.

A good general overview of Acoustic-Doppler Velocimetry is provided by Lohrmann et al. (1994) with further information on the ADV used here available from Nortek (Nortek-AS, 2004).

Along with velocity, the ADV measures two other quantities which relate to the quality of each measurement being taken. For each sample, signal to noise ratio (SNR) and correlation are given. Signal to noise ratio was maintained above 15 throughout this experiment in line with the work of Cea et al. (2007), Rusello et al. (2006) and Lohrmann et al. (1994). Correlation was used to filter the data from the ADV throughout. Martin et al. (2002) and Rusello et al. (2006) recommended 70% as the threshold value but it was found that for these experiments a 75% threshold was more suitable, Fig. 6.

The 75% threshold was found to give the best compromise of data quality and retained samples especially while considering turbulent intensity, Fig. 7.

Correlation filtering was found to be ineffective when large bubbles were present in the flow as per Cea et al. (2007). The experimental arrangement here should however minimise bubble entrainment.

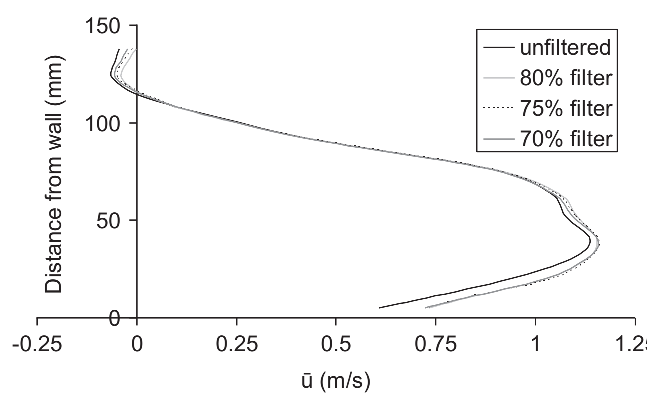

Fig. 6. Comparison of velocity profiles at x=65 mm test S1 for different filtering thresholds.

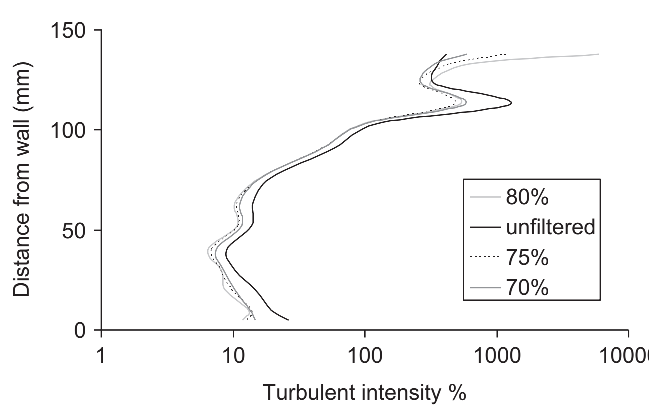

Fig. 7. Comparison of turbulent intensity profiles at x=65 mm test S2 for different filtering thresholds.

Seeding is necessary for the ADV to operate in a laboratory environment. Here it was provided by using neutrally buoyant hollow glass spheres with a mean diameter of 11.7 μm. Seeding density was found by adding seeding until the correlation value stabilised. The test tank was also swept before testing to re-suspend heavier particles within the flow (Nortek-AS, 2004).

2.2. Experimental uncertainty

The geometrical tolerance of the machined parts was less than ±0.1 mm. The impeller/duct gap was 2 mm ± 0.5 mm with the impeller centered within 1 mm. The positional accuracy of the automated gantry on which the ADV was mounted was ±0.1 mm. Rusello et al. (2006) quoted the error of the ADV velocity measurements to be a maximum of 4% when compared to a PIV system. The accumulated uncertainty typical of a PIV system is at ±5% (Oweis et al., 2006a). The manufacturer calibrates the device in a low turbulence towing tank and quote the accuracy of velocity measurements provided by the ADV to be ±0.5% (Nortek-AS, 2004). However this is not given in relation to a speed range or turbulence level. Temperature was measured using a thermocouple mounted inside the ADV with a quoted accuracy of ±0.1 °C.

3. Results

To provide a series of results the impeller was run at three different speeds;, the details of these tests are described in Table 1.

Approximate average velocity in Table 1 was constructed using mean point measurements from the results at $x = 780$ mm.

Due to the testing procedure there was a small change in temperature during the tests with a minimum temperature of 19.3 °C and a maximum of 22.5 °C.

The level of turbulence present in a conditioned impeller wake is significantly higher than in any published work where an ADV is used. This experiment takes place in a pipe and therefore the volume flow rate should be the same at any pipe cross section. The measurements here do not show this which indicates a measurement error more than the one discussed in Section 2.2. It would appear that when turbulence reaches a certain level the ADV begins to under-read the velocity. This can be observed from the average velocity for each of the velocity profiles taken across the pipe at each x locations, Table 2.

The true average velocity of the pipe flow can be taken from the stations furthest downstream of the honeycomb as these are least affected by turbulence. The average span-wise velocity can be seen to have stabilised by $x = 480$ mm and therefore this value is taken as the true average span-wise velocity. This value can be seen in the last row of Table 2.

The under-reading of velocity shows a somewhat approximate linear relationship with the turbulent intensity. This can be seen in Fig. 8 where the error is given by dividing the true average velocity by the measured average velocity.

If tests S2 and S3 are analysed in the same way the same linear relationship is found. This simple linear relationship indicates that a simple correction equation could be applied for ADV measurements. To develop this equation further it would be prudent to do a point-to-point calibration against a laser doppler velocimeter or equivalent point measurement device which has been proved accurate in flows with a corresponding turbulence level seen here.

Table 1
Test cases.

Test	Approximate average velocity u (m/s)
S1	0.78
S2	0.66
S3	0.51

Table 2
Profile data at each measurement station.

X (mm)	u av S1 (m/s)	S1 TI%	n S1	u av S2 (m/s)	TI% S2	n S2	u av S3 (m/s)	TI% S3	n S3
10	0.56	23.9	1.39	0.42	36.9	1.55	0.34	31.7	1.48
35	0.62	21.5	1.25	0.47	25.6	1.40	0.30	41.5	1.69
75	0.63	21.3	1.24	0.40	28.2	1.63	0.33	33.1	1.53
125	0.64	20.6	1.23	0.50	22.0	1.31	0.36	27.1	1.42
200	0.67	19.6	1.16	0.51	21.2	1.30	0.42	23.6	1.22
275	0.68	18.3	1.15	0.56	17.9	1.18	0.44	19.6	1.14
380	0.76	14.6	1.03	0.64	15.6	1.03	0.46	17.7	1.10
480	0.80	15.0	0.98	0.65	14.9	1.02	0.47	16.1	1.08
595	0.77	14.0	1.01	0.64	14.4	1.04	0.47	15.8	1.08
750	0.78	13.6	1.00	0.66	14.0	1.00	0.51	14.6	1.00
u av true	0.78			0.66			0.51		

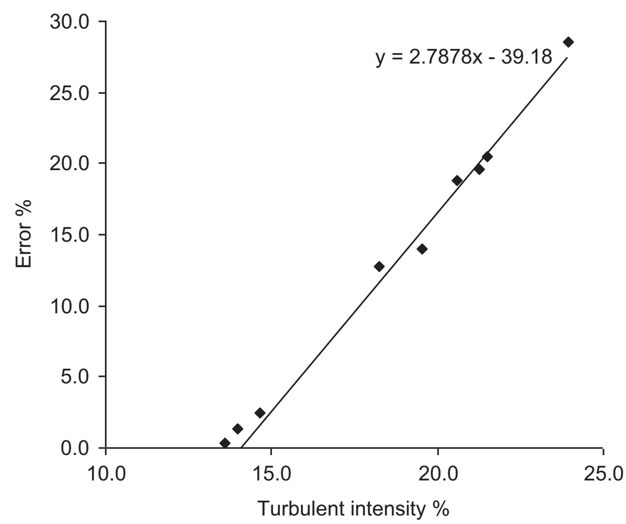

Fig. 8. Average error versus average turbulent intensity for each span-wise profile for case S1.

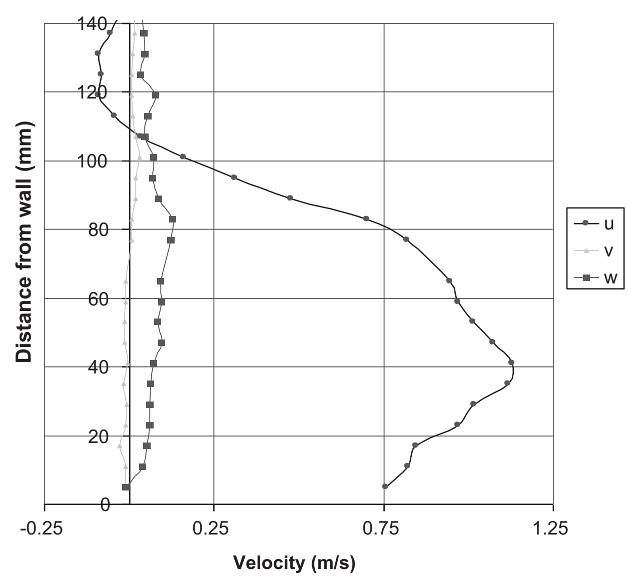

Fig. 9. Mean velocities versus distance from wall at $x = 40$ mm, Test S1.

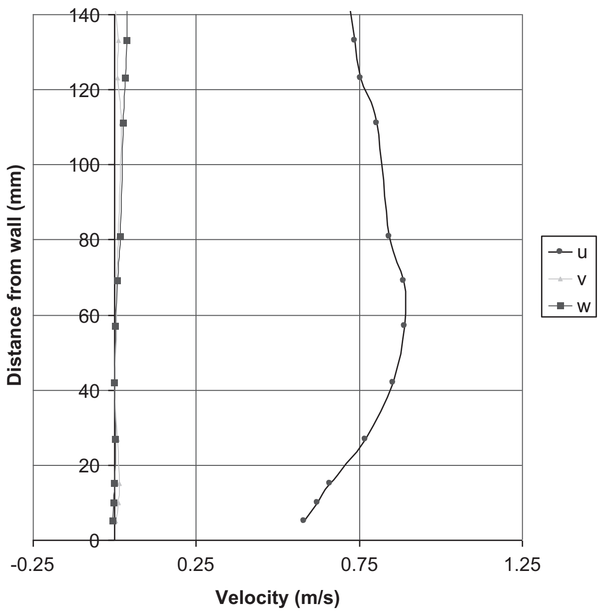

Fig. 10. Mean velocities versus distance from wall at x=780 mm, Test S1.

Although the above findings could be used to correct the ADV velocity measurements, another approach is possible. Using the fact that the measurements were taken in a pipe and span-wise average velocity is constant, the point velocities can be normalised to give the correct average velocity. In Figs. 11–13 the point velocities are normalised to give an average span-wise velocity matching the true average by multiplying the measured velocity by a constant. The constant for each span-wise profile is given by n in Table 2. The smooth lines created by the point data given in Figs. 11–13 indicate that the point measurements taken by the ADV are accurate and consistent.

The first column of Table 2 gives the x position in the pipe. Columns 2, 5 and 8 give the average velocity with columns 3, 6 and 9 showing the average turbulent intensity. Columns 4, 7 and 10 give the error in the average velocity by dividing the measured average velocity for the whole profile by the true average velocity.

3.1. 3D flows

Although the honeycomb should act to remove the y and z components of velocity from the flow, measurable y and z velocities may still be present due to the reversing flow caused by the hub effect visible at x=40 mm in Figs. 11–13. From

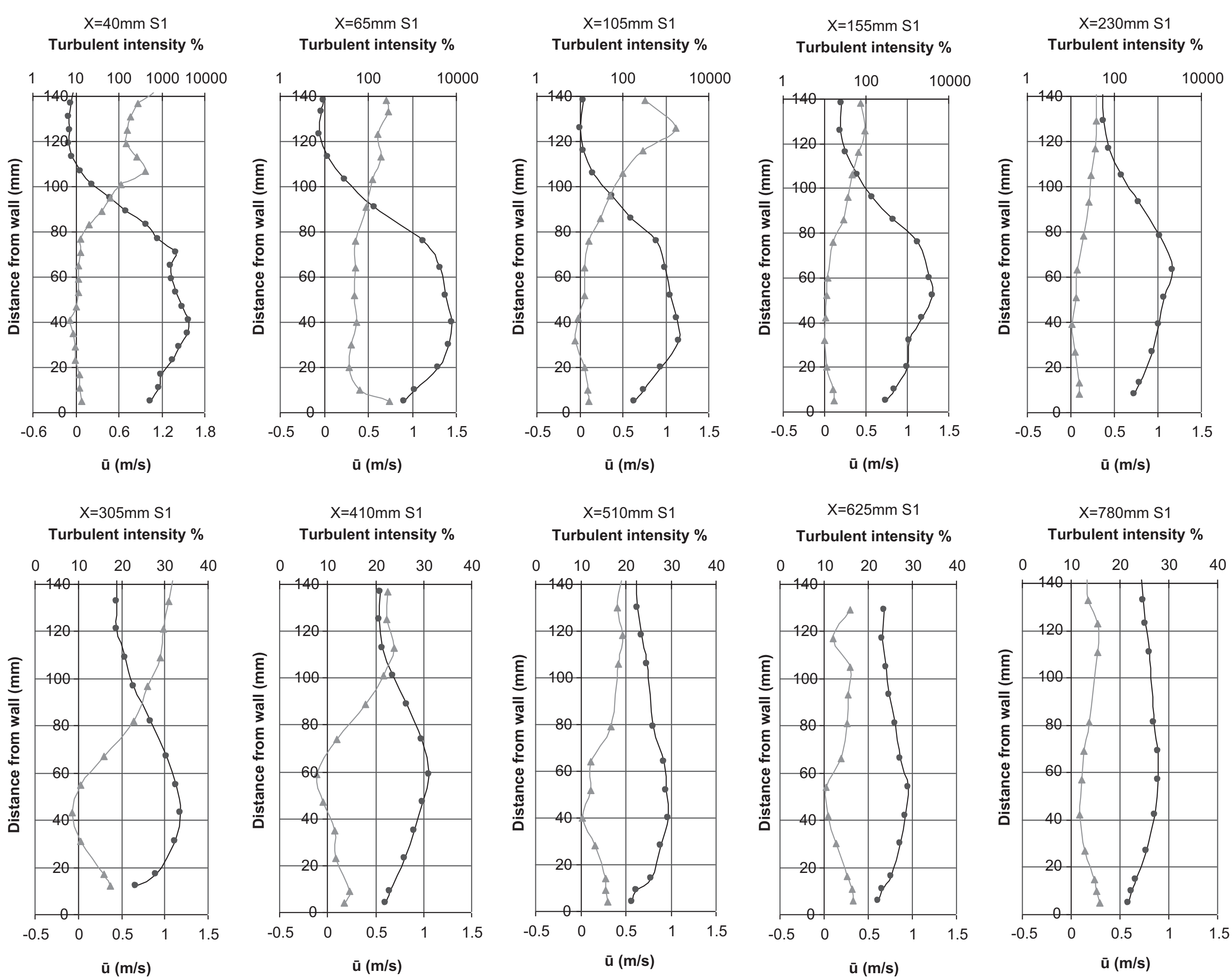

Fig. 11. Mean velocity u and turbulent intensity versus distance from wall for various X positions, impeller speed=1. The gray line is turbulent intensity and the black is velocity.

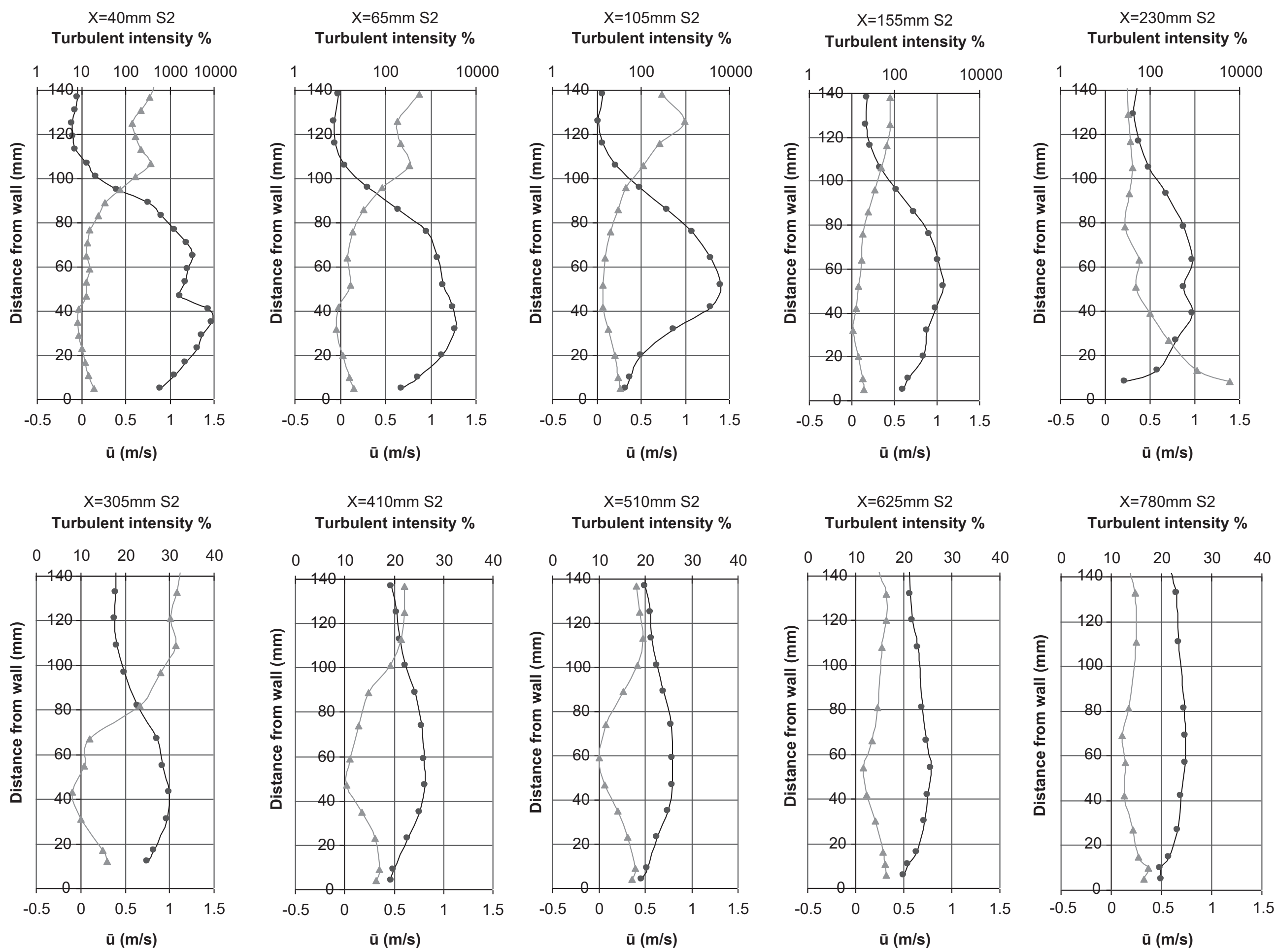

Fig. 12. Mean velocity u and turbulent intensity versus distance from wall for various X positions, impeller speed$=2$. The gray line is turbulent intensity and the black is velocity.

examination of velocity vectors in the y direction, Fig. 9, it is clear the y velocity is negligible. By the end of the measurement range at $x=780$ mm the maximum y component measurement has dropped below 1% of the x component of velocity. From this it can be asserted that all impeller induced swirl has been removed by the flow conditioning.

From Fig. 9 the z component of velocity is more significant than the y component of velocity and is comparable with the x component in the hub-affected region. The turbulent intensity in this region is 200% indicating a highly fluctuating velocity in the z direction. At the furthest measured point from the honeycomb measured the maximum Z component is only 5% of the x component and is insignificant, Fig. 10.

3.2. Wake evolution

The characteristics of an unconditioned impeller wake are recognisable from the results presented here. At the first measurement station ($x=40$ mm, Fig. 11), the maximum velocity is located at the point at which the impeller is designed to give the highest thrust $r/R=0.725$. From this point the velocity drops until it reaches the boundary layer at the wall. At the center of the duct there is a large hub-affected zone where some reversing flow is seen. Although the general profile seen in open impeller studies such as Felli et al. (2002) and Stella et al. (2000a) is similar to that reported here, neither report reversing flow. As the flow moves downstream of the honeycomb it develops and smoothes, moving towards a normal pipe flow profile, though it is not fully developed by the end of the measurement region for any setting (Figs. 11–13).

Turbulence also decays as the flow moves downstream with the maximum value in the hub affected region. Turbulent intensity is a less meaningful measurement in cases where mean velocity is low but velocity fluctuation is high such as in the hub affected region, e.g. Fig. 11, $x=40$. In these areas turbulent kinetic energy or Reynolds stresses would be more useful. To reliably obtain a measurement of turbulent kinetic energy or Reynolds stresses at least 50,000 measurements would be required (Chanson et al., 2007).

An impeller of the type used here induces a pulsation into the flow during the blade passage. Studies into unconditioned propeller wakes such as Felli et al. (2002) and Stella et al. (2000a) record propeller position so this effect can be extracted from the data. If a significant pulse was present after the honeycomb it should be detected by performing a fast Fourier transform frequency domain analysis on the data. Although at 50 Hz measurement frequency of the impeller blade passage should be detectable, no dominant frequencies were found at $x=40$ mm and $x=780$ mm when this analysis was performed.

4. Conclusions

Wake evolution is measured from a conditioned axial flow impeller using an Acoustic-Doppler Velocimeter (ADV). Flow conditioning was provided by honeycomb which reduced the swirl induced from the impeller to insignificant levels. Velocity

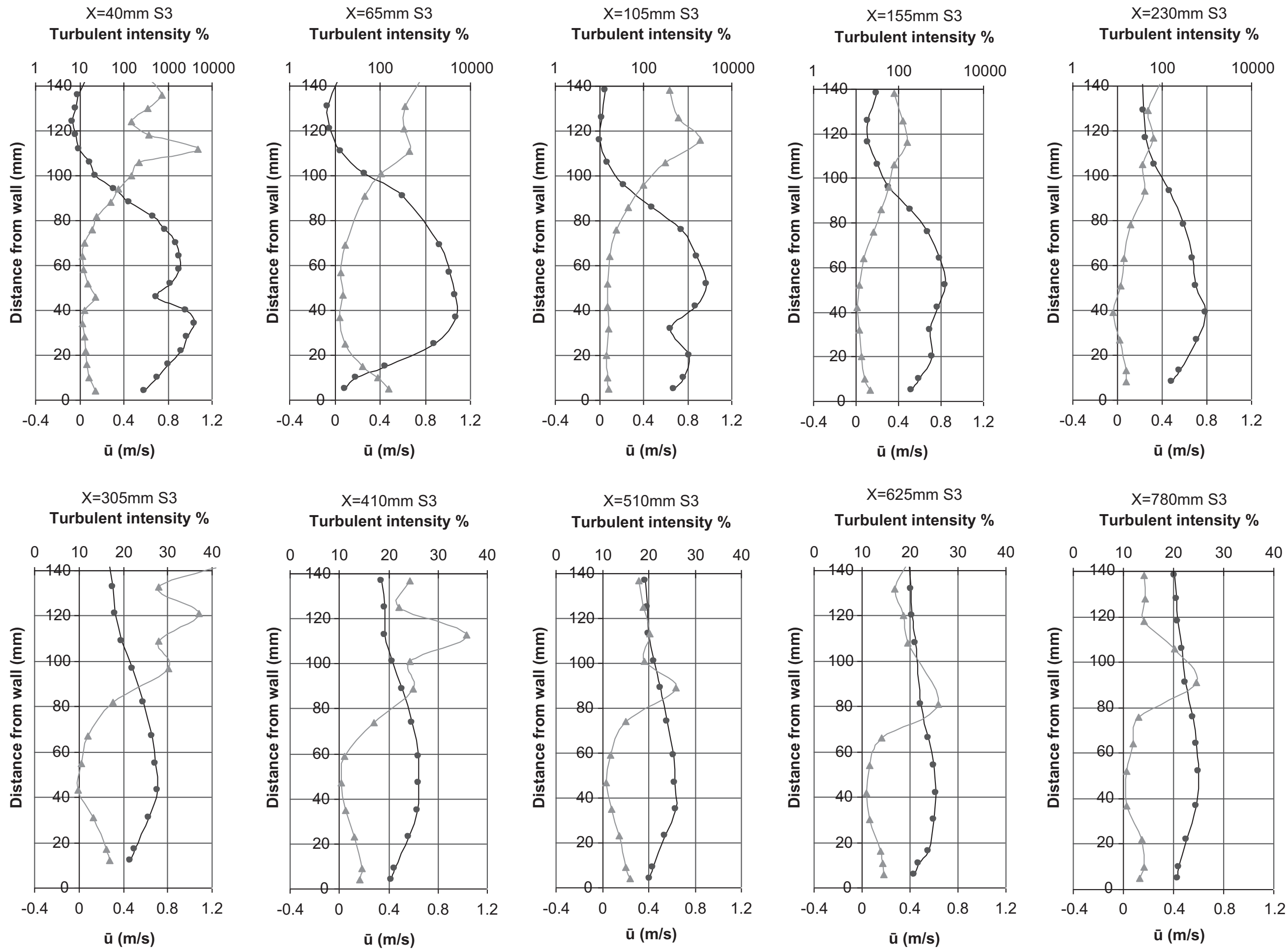

Fig. 13. Mean velocity u and turbulent intensity versus distance from wall for various X positions, impeller speed = 3. The gray line is turbulent intensity and the black is velocity.

profiles downstream of the honeycomb were consistent with propellers in most areas. The ADV provided a high enough sample rate to give a basic characterisation of the turbulence present but exhibited a measurement error at higher turbulence levels. Fortunately this error was found to have a simple relationship with turbulence and a correction method is proposed.

The wake evolution data here should enable the development of numerical models to support the design of future current and wave testing tanks.

Acknowledgments

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